Annual nutrients export modelling by analysis of landuse and topographic information: case of a small Mediterranean catchment

S. Payraudeau*, M.G. Tournoud, F. Cernesson* and B. Picot*****

* Laboratoire Structures et Systèmes Spatiaux, CEMAGREF-ENGREF, 500 J.F. Breton 34093 Montpellier, France

** Laboratoire Hydrosciences, Université Montpellier 2 – CNRS – IRD (UMR5569), cc056 34095 Montpellier Cedex 5, France

*** Département Sciences de l'Environnement et Santé Publique, Université Montpellier 1 et 2 – CNRS (UMR5556), Avenue Charles Flahaut 34060 Montpellier Cedex1, France

Abstract The preservation of water bodies from eutrophication implies accurate estimation of phosphorus and nitrogen loads and the control of nutrient production on a catchment scale. In this paper, a simple tool for the modelling of annual nutrient loads is presented. It is implemented in ARC/INFO GIS using Arc Macro Language (AML). The use of a GIS is justified as the spatial characteristics of the catchment area (land use, industrial wastewater location) dictate water quality. The annual nutrient loads are worked out on the catchment scale, using existing GIS routines together with specific routines developed in AML for hydrological and water quality modelling purposes. The catchment area is divided into hydrological subcatchments with relatively homogeneous spatial characteristics. Each subcatchment is linked to a specific nutrient export potential. These nutrient loads, calculated on a subcatchment-by-subcatchment basis, are conveyed to the outlet of the catchment and allow annual nutrient load estimation. A comparison with a water monitoring study is conducted to verify the adequation of modelling results for phosphorus and nitrogen loads.

Keywords Geographic Information System; nutrient; spatial analysis; water quality modelling; watershed

Water Science and Technology **Vol 44 No 2–3 pp 321–327** © IWA Publishing 2001

Introduction

Preservation of water quality requires the management of nutrients on a meaningful scale from a hydrological point of view: at catchment level. This global approach must be developed taking into account the water paths taken through the subcatchment slopes and the channel watercourses (Villeneuve *et al.*, 1998). Within the watershed, the management of nutrients implies the identification of the point sources such as municipal and industrial wastewater plants, together with the non-point sources of pollution, like natural, agricultural and urban areas.

The modelling of nutrient loads generated at the outlet of the watershed requires a tool capable of linking the land uses to the contaminants production and to transfer the pollution to the river. This tool must integrate geographical information (land uses, topography, . . .) and hydro-chemical modelling in a database management system such as a Geographic Information System (GIS) (Cluis, 1995). The model development must be guided by four principles which are: reduced number of parameters, modesty, accuracy of data and testability (Moore *et al.*, 1993).

This approach means choosing the spatial structure of the hydro-chemical model. There are four main model structures which are commonly used: lumped model (Shiiba *et al.*, 1996), model based on hydrological "homogeneous" subcatchment delineation (Jeton and Larue-Smith, 1993; Flügel, 1996), grid-based model (Cluis *et al.*, 1996) and tin-based model (Vieux, 1991). In this study, our model is based on delineation of nutrient production units through analysis focused on hydrological functioning. Therefore, the catchment is divided into smaller subcatchments and reaches. This delineation allows a distinction to be made between production function for subcatchments and transfer function for reaches.

This hydrological delineation is used to model the nutrient dynamics on various temporal scales. For each scale, transfer and nutrient production functions must be adapted to the main hydrological processes. In this paper, we propose to use this spatial structure to estimate annual nutrient export. Spatial information on land use, topography and point source locations (urban and industrial) is integrated by the GIS.

Different methods can be used to identify pollution sources and annual nutrient export. One method uses loading functions to relate annual runoff and annual nutrient export (Haith and Shoemaker, 1987). The parameter of this empirical function is defined for each land use type. We chose the export coefficient method to evaluate annual nutrient exports (Worrall and Burt, 1999). Each land use is defined by annual potential nutrient exports in kg/ha/year. These export coefficients are obtained in the literature or from catchment scale studies (Benneton, 1984).

Nutrient modelling and annual export estimates were all conducted within the Pallas watershed, (50 km^2), located in the Thau lagoon catchment area (France). The results of this modelling approach were compared to the results of the monitoring study (1994–1996) conducted at the outlet of this watershed.

Materials and methods

The database management system built for annual nutrient outputs modelling uses the Geographic Information System ARC/INFO software (Environment Systems Research Institute, Redlands, California), on a SUN SPARC station platform (SUN Microsystems, Mountain View, California) using a UNIX operating system.

This software was chosen because of its capacity to define and model a great number of objects : lines, polygons and points. Although this software was not primarily developed for hydrological purposes, some of its routines can be used for geomorphologic and hydrographic network studies. Moreover specific hydrological routines may be conceived and directly implemented using its own programming language (the Arc Macro Language, AML).

The database created requires a Digital Elevation Model (DEM), digital line coverage that locates hydrographic network, pollution point source coverage and land use coverage (determined by satellite imagery). Coverage is defined as a data set describing the spatial variation concerning one study area theme. Each coverage concerns information on the type of data, (line, polygon, point or grid cell), defined as thematic attributes and the geocodes of the data (Nuckols *et al*., 1996).

The first step was to divide the catchment area into nutrient production units through analysis focused on hydrological functioning. This step involves extracting subcatchment delineations using information obtained with the digital elevation model. In ARC/INFO a specific module (GRID) offers several hydrologically relevant functions by which a catchment can be divided into smaller sub-basins and reaches (Thieken *et al*., 1999). In order to derive channel network from the DEM, it is assumed that there is flow in a channel if its upstream area exceeds a critical threshold. In this case, the cell is considered as a channel segment. This value must be estimated using hydrographic network cover, which shows the real geometry of the river. The channel network obtained from the DEM must be comparable to the hydrographic network. At the channel junctions and sources, such as river source or pollution point source, the "contributing subareas" are calculated using the watershed function of ARC/INFO. This function requires a step-by-step calculation. The creation of an AML program automates this function for all nodes of the channel.

The second step of our approach involves the definition of land uses on each subcatchment and the location of nutrient point sources. Nutrient export depends on hydrological conditions, climatic characteristics, geology, topography, soil type and land management practices. However, on an annual scale, land use is the most important catchment characteristic when estimating nutrient non-point source (Worrall and Burt, 1999). So, in our approach, calculations assume nutrient outputs to be solely dependent on human activity or land use. Each land use or activity has a specific "nutrient generation rate" determined from field studies described in the existing literature (Benneton, 1984; Young *et al*, 1995; Worral and Burt, 1999).

Therefore, our modelling approach necessitates having in-depth knowledge of:

- land use and the associated nutrient production rates to predict the annual nutrient outputs from the non-point sources.
- point sources locations in the catchment to estimate total nutrient exports.

Remote sensing data is a valuable source of information for land use modelling (Schultz, 1993). The choice of sensors is dictated by the time and space resolution needed for interpretation. The sensor chosen must permit a suitable classification of land uses. The quality of this classification will depend on the land use types, the quantity of images available and the dates on which they were taken as well as the classification technique used. Ambiguities in interpretation can be reduced by using field information to improve classification. The number of land use categories depends on the type of hydrologic model used.

In annual nutrient exports modelling, this number must permit the estimation of total nutrient export from a catchment and compare the possible effects of land use changes. Urban areas, farming areas, grasslands and forests are distinguished. A distinction between types of farming can be made to obtain a best estimate of potential nutrient export.

The contribution of pollution point sources requires the location of municipal and industrial wastewater plants. Each subcatchment is associated by nutrient point sources.

For each subcatchment, the last step consists of relating nutrient generation rates to land uses and to point source types. Nutrient generation rate data can be obtained by field experiments. This data is at present very scarce. A viable alternative is the considerable body of existing literature that allows the estimation of annual nutrient loads for various land uses and point sources. Loads are calculated for each category of land use located on a subcatchment. What is obtained is subcatchment delineation with annual nitrogen and phosphorus loads.

Spatial intersection between hydrographic network coverage and subcatchment coverage help us define the links between the subcatchments and the reaches. This method relates surface attributes, such as nutrient loads, to linear objects such as reach. A specific function is required to estimate for each reach the nutrient loads accumulated upstream. This function is available in an ARC/INFO module (NETWORK).

The last step could consist of implementing a river nutrient-decay model to include river purification capacity (Nuckols *et al.*, 1996).

All these steps are made in an annual nutrient load model. Input information consists of a digital elevation model, land use coverage and nutrient point sources data. The parameters of this model are the nutrient generation rates for the various land use categories and point sources. Output results give subcatchment coverage with annual phosphorus and nitrogen loads for each unit. The model allows a representation of the hydrographic network nutrient loads, with for each reach, the subcatchment associated nutrient loads and upstream pollution pressure.

Application and results

The modelling of annual nutrient loads is conducted within the watershed of Pallas located in the catchment area of the Thau lagoon (France) (see Figure 1). This watershed is

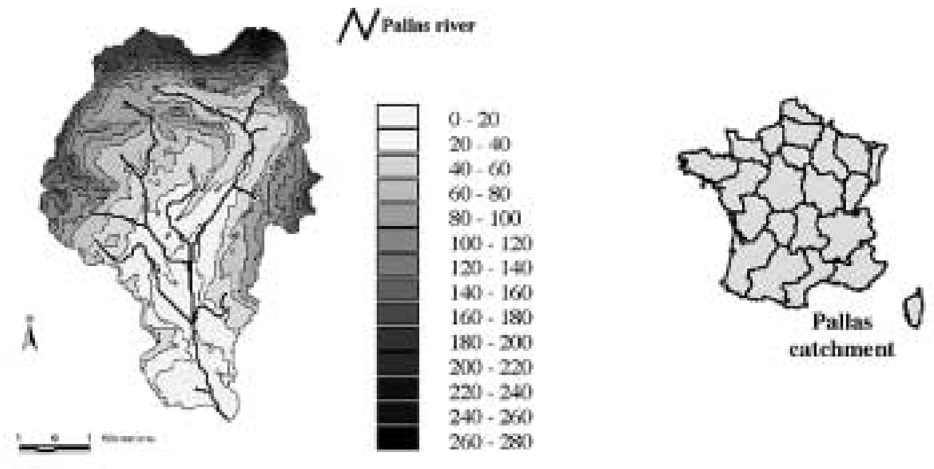


Figure 1 Pallas catchment location (Hérault, France)

characterised by a sparse population. The river Pallas crosses three small urban areas and receives the municipal wastewaters of a population of 1600.

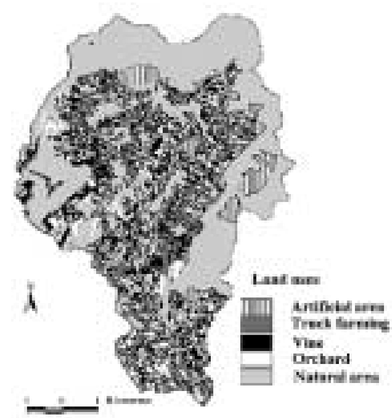
The database created for this study includes the digital elevation model (DEM) with a horizontal resolution of 50 m, the hydrographic network (at 1:50,000 scale), the pollution point sources database (at 1:50,000 scale) and the land uses coverage classified from a 1996 SPOT image with a resolution of 20 m.

The annual nutrients loads generated on a subcatchment-by-subcatchment basis are showed in the Figure 3. For each reach, upstream nutrient loads have been calculated.

Each subcatchment nutrient unit load is transferred to its corresponding reach and accumulates from upstream to downstream. The results obtained for the hydrographic network are illustrated in Figure 4.

Testability is one of the most important principles that should guide model development. The testability of annual nutrient load estimates requires annual water quality monitoring.

Pallas river water quality was monitored from September 1994 to May 1996 at the outlet of the catchment. Samples were taken in shallow water twice a month and once every hour



Land uses	Nitrogen generation rate (kg/ha/year)	Phosphorus generation rate (kg/ha/year)
Artificial area	10	2
Truck farming	10	1
Vine	5	1
Orchard	10	1
Natural area	0.2	0.1

Figure 2 Land uses of Pallas watershed obtained from SPOT classification, an associated specific "nutrient generation rate" (Benneton, 1984)

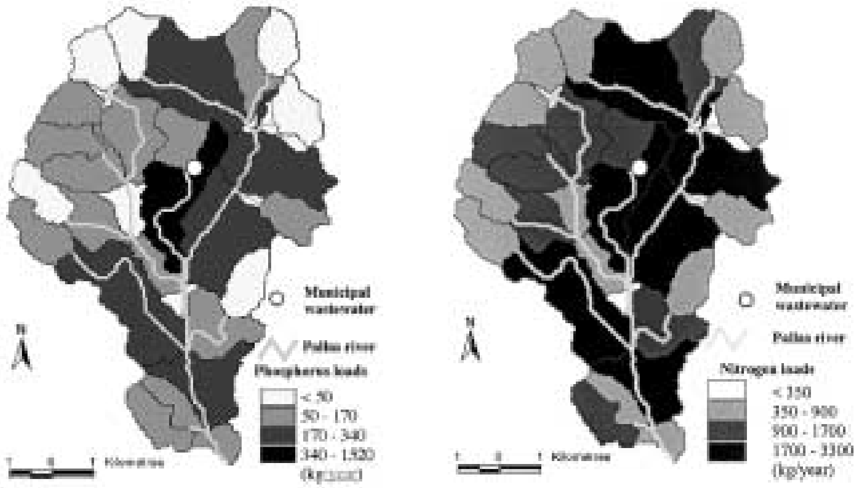


Figure 3 Subcatchment delineation with annual phosphorus and nitrogen loads estimation (kg/year)

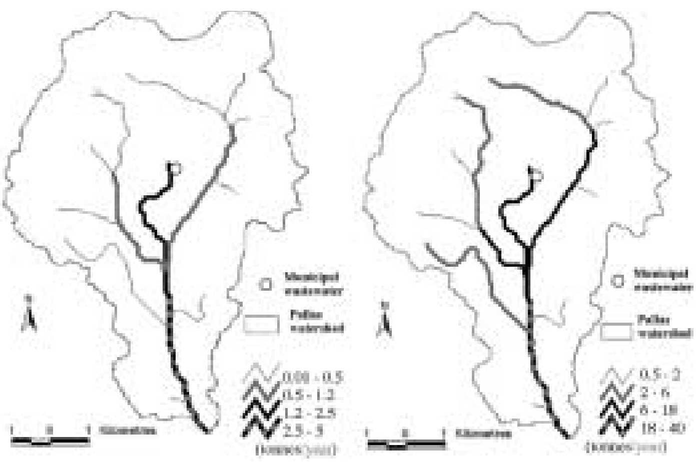


Figure 4 Hydrographic network with annual phosphorus and nitrogen quantity estimation (tonnes/year)

during three flow events. Each sample was analysed to determine nitrogen and phosphorus concentrations. So, ortho-phosphorus (PO_4^{3+}), total phosphorus (Pt), kjeldahl nitrogen (NK), ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-) were analysed using standard methods (APHA, 1992). The flow discharge was also continuously monitored (Contrat pour l'étang de Thau, 1997).

An extrapolation of the data allows us to estimate annual phosphorus and nitrogen outputs at the outlet of the Pallas watershed. This annual nutrient load was estimated with a 50% uncertainty. The comparison between the annual nutrient loads calculated with the modelling approach and estimated by the experimental approach is not a testability step in the model development. In fact, in our modelling approach, nutrient production rates for the various activities are obtained from the literature and used to determine production for an average year while the results from water monitoring characterise annual nutrient exports for two particular years. In conclusion, the following comparison (Figure 5) only concerns the annual nutrient exports order of magnitude for the Pallas river. The results from the two approaches concur.

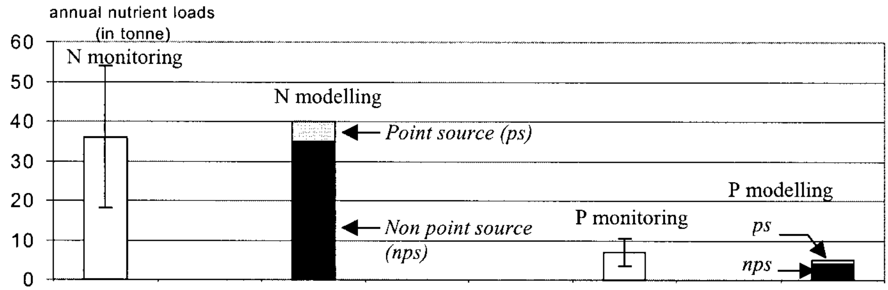


Figure 5 Comparison between annual nutrient load estimates by our modelling approach and by water quality monitoring

Discussion and conclusions

The estimates of average annual catchment nutrients loads constitute the starting point for strategic decision making in water quality management. The modelling approach at catchment scale takes into account the hydrological functioning of the catchment. It is based on the delineation of meaningful hydrological objects such as subcatchments and reaches for which nutrient loads can be calculated.

The comparison between results obtained from the model and experimental data has proven to be quite tricky. However, we have shown that on an annual scale the results from our model have the same order of magnitude as the experimental results. The model, which is described in this paper, is therefore suitable to estimate the nutrient load potential of a catchment on an annual scale.

Our modelling approach is a useful tool for water quality management as it answers two questions: where and how many nutrients are likely to be produced in a catchment area and discharged in the river? The results obtained from the model, such as those seen in Figure 3, allow the classification of subcatchment by their potential nutrient exports. This classification should help those concerned in policy making for global water quality management. Moreover, the classification of channel networks according to its upstream nutrient pressure is also possible with this method as shown in Figure 4. The mapping of this nutrient pressure is crucial for better river management. Finally, this spatial classification can help when choosing particular subcatchments or reaches to conduct quality water monitoring studies in the catchment area.

This paper shows the first application of hydrological segmentation on reach and subcatchment. Our approach can be improved by using a nutrient decay model to represent chemical processes in rivers (Young *et al.*, 1995). Our paper also underlines that the first step for effective catchment water quality management is the calculation of annual nutrient exports. Furthermore nutrient flux dynamics and variability must be evaluated on a shorter time scale. The results of water quality monitoring show that 66% of annual phosphorus flux and 41% of annual nitrogen is obtained for flood events. Flood events only represent 3% of time during the monitoring study. This particular hydrological functioning of catchment is due to extremely variable climatic conditions. Thus, storm flows can occur after a long period of low water levels.

In order to perform nutrient flux modelling on a flood event scale, production and transfer functions must be adapted to this time scale. The spatial structure of the model developed in this paper will be used to model changes in nutrient levels. The GIS will allow the integration of hydrological parameters for each subcatchment such as the soil analysis, land uses and slope data. Similarly, characteristics of each reach of hydrographic network (reach slope, length, depth …) will be integrated in GIS.

In conclusion, this paper shows the feasibility of the nutrient generation rate method for estimating catchment nutrient export at an annual scale. However, in the Mediterranean context, given the great variability of rainfall event, it is necessary to model at a flood event scale, which will be the next step of our work.

Acknowledgements

The authors would like to acknowledge IGN (Geographic National Institute) for the use of digital elevation model and for database BDCARTO, Departmental administration for point pollution coverage and SIG L-R for land uses coverage.

References

APHA, AWWA, WEF (1992). *Standard methods for the examination of water and wastewater*.18th edition.Washington, DC: American Public Health Association.

Benneton, J. C. (1984). *Eutrophisation des plans d'eau: inventaire des principales sources de substances nutritives azotées et phosphorées* – étude bibliographique, 68 p.

Cluis, D. (1995). Specifications of a loading model for assessing optimal interventions at the watershed scale. *The International Symposium on Water Quality Modelling*, Orlando, Floride, April 1995. ASAE Publication, pp 521–529.

Cluis, D., Martz, L., Quentin, E. and Rechatin, C. (1996). Coupling GIS and DEM to classify the Hortonian pathways of non-point sources to the hydrographic network. *HydroGIS'96: Application of Geographic Information Systems in hydrology and water resources management*, Vienna, Austria, April 1996. no 235. IAHS Publication, pp 37–43.

Contrat pour l'étang de Thau (1997). Suivi des apports du bassin versant de l'étang de Thau et des échanges avec la mer par les canaux de Sète. Laboratoire Géofluide-Bassins-Eau/Laboratoire d'hydrobiologie marine et continentale/Département Sciences de l'Environnement et santé publique. Montpellier, 175 p.

Flügel, W.A. (1996). Application of GIS to derive Hydrological Response Units for hydrological modelling in the Brol catchment, Germany. *HydroGIS'96: Application of Geographic Information Systems in hydrology and water resources management*, Vienna, Austria, April 1996. no 235. IAHS Publication, pp 413–420.

Haith, D.A. and Shoemaker, L.L. (1987). Generalised watershed loading functions for stream flow nutrients. *Water Resources Bulletin*, Vol 23, pp 471–478.

Jeton, A.E. and Larue-smith, J. (1993). Development of watershed models for two Sierra Nevada basins using a geographic information system. *Water resources bulletin*, Vol 29, no 6, pp 923–932.

Moore, I.D., Turner, A.K. Wilson, J.P., Jenson, S.K. and Band, L.E. (1993). GIS and land- surface-subsurface process modelling. In: *Environmental modelling with GIS*, pp 197–230.

Nuckols, J.R., Ellington, D. and Faidi, H. (1996). Addressing the non-point source implications of conjunctive water use with a geographic information system (GIS). *HydroGIS'96: Application of Geographic Information Systems in hydrology and water resources management*, Vienna, Austria, April 1996. no 235. IAHS Publication, pp 341–348.

Schultz, G.A. (1993). Application of GIS and remote sensing in hydrology. *HydroGIS'93: Application of Geographic Information Systems in hydrology and water resources management*, Vienna, Austria, April 1993. no 211. IAHS Publication, pp 127–140.

Shiiba, M., Ichikawa, Y., Ikebuchi, S., Tachikawa, Y. and Takasao, T. (1996). Scale-up of a runoff model using GIS and an object-oriented hydrological modelling system. *HydroGIS'96: Application of Geographic Information Systems in hydrology and water resources management*, Vienna, Austria, April 1996. no 235, IAHS Publication. pp 63–70.

Thieken, A.H., Lucke, A., Diekkruger, B. and Richter, O. (1999). Scaling input data by GIS for hydrological modelling. *Hydrological Processes*, Vol 13, pp 611–630.

Vieux, B.E., (1991). Geographic information systems and non-point source water quality and quantity modelling. *Hydrological Processes*, Vol 5, pp 101–113.

Villeneuve, J.P., Hubert, P., Mailhot, A. and Rousseau, A. (1998). La modélisation hydrologique et la gestion de l'eau. *Revue des sciences de l'eau*, Vol no special (1998), pp 19–39.

Worrall, F. and Burt, T.P. (1999). The impact of land-use change on water quality at the catchment scale: the use of export coefficient and structural models. *Journal of Hydrology*, Vol 221, pp 75–90.

Young, W.J., Farley, T.F. and Davis, J.R. (1995). Nutrient management at the catchment scale using a decision support system. *Wat. Sci. Tech.*, Vol 32, no 5–6, pp 277–282.